Unified Parameterization of the Marine Boundary Layer

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LONG-TERM GOALS

The long term goals of this effort are (i) the development of a unified parameterization for the marine boundary layer; (ii) the implementation of this new parameterization in the US Navy COAMPS mesoscale model; and (iii) the transition of this new version of the COAMPS model into operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC).

OBJECTIVES

The objectives of this project are: i) to develop a unified parameterization for the Marine Boundary Layer (MBL) and ii) to implement and test this parameterization in the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS®[1]).

APPROACH

This unified boundary layer parameterization will be based on two main components: (i) the Eddy-Diffusivity Mass-Flux (EDMF) parameterization of boundary layer mixing; and (ii) the Probability Density Function (PDF) cloud parameterization.

Together these two concepts allow for the unification of MBL parameterization in one single scheme. They also allow for the development of physically-based strategies that take into account the horizontal grid-size in the parameterization framework. Such a development would lead to a resolution-dependent MBL parameterization that would adjust itself to the horizontal grid resolution (e.g., tending asymptotically to a Large Eddy Simulation (LES) model parameterization for very high horizontal resolutions of the order of 10 to 100 m).

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[1] COAMPS® is a trademark of the Naval Research Laboratory.

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14. ABSTRACT

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Key personnel:

J. Teixeira (JPL/Caltech) uses his expertise in cloud and boundary layer parameterizations to guide the development and implementation of the EDMF/PDF parameterization.

J. Doyle (NRL) uses his expertise in mesoscale modeling to assist with the investigations related to COAMPS within the context of his existing ONR project.

M. Witek (Caltech Postdoc) performs the development and implementation of the EDMF parameterization in the COAMPS model.

WORK COMPLETED

Tasks completed:

- Performed EDMF single-column studies with decomposition between large scales (parameterized by the MF term) and small scales (ED) for dry convective boundary layer cases;
- Implemented and evaluated new EDMF parameterization in COAMPS model.

RESULTS

Description of achievements in the fiscal year can be classified in two stages:

1. EDMF in single-column (1-D) model
2. EDMF in COAMPS

During the first stage investigations of the EDMF parameterization in single column mode were performed. This study was performed in order to improve the formulation of the EDMF approach as well as to assess model sensitivity to key EDMF parameters. During the second stage we addressed the details of the EDMF implementation in COAMPS and compared model simulations with observations of the boundary layer structure. Both subjects are described in detail in the following paragraphs.

EDMF in 1-D model

General equations

The prognostic equations for the potential temperature and specific humidity represented by a generic variable $\phi \in (\theta, q_v)$ are

$$\frac{\partial \overline{\phi}}{\partial t} = -\frac{\partial \overline{w'\phi'}}{\partial z} + F_{\phi}, \qquad (1)$$

where w is the vertical velocity, primes denote perturbations from the mean values and F_ϕ is a source term. Vertical turbulent fluxes are parameterized in terms of the eddy-diffusivity mass-flux approach (following e.g. Siebesma et al. 2007)

$$\overline{w'\phi'} \cong -K_\phi \frac{\partial \overline{\phi}}{\partial z} + M\left(\phi_u - \overline{\phi}\right), \tag{2}$$

where K_ϕ is the diffusion coefficient for a variable ϕ, ϕ_u is the updraft value of ϕ and $M = a_u w_u$ is the mass flux, with a_u representing the fraction area of an updraft. Similar prognostic equations apply to horizontal components of the velocity (u, v), but the turbulent transport of momentum is parameterized only with the eddy-diffusivity method (there is no mass-flux term in $\overline{u'w'}$ and $\overline{v'w'}$ parameterizations).

A prognostic equation for the turbulent kinetic energy (TKE) takes the form

$$\frac{\partial e}{\partial t} = -\frac{\partial}{\partial z}\left(-K_z \frac{\partial e}{\partial z}\right) + \frac{g}{\overline{\theta}} \overline{w'\theta_v'} - \overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z} - D\,, \tag{3}$$

where e is the TKE, K_e is the diffusion coefficient for e, g is the acceleration due to gravity and D is the dissipation term.

Parameterizations

In order to solve the prognostic equations (1) and (3) presented above, additional equations and parameterizations need to be introduced. These include parameterizations of the diffusion coefficients (K_ϕ, K_e), the dissipation term ϵ, and diagnostic equations for the updraft values ϕ_u and the updraft vertical velocity w_u, which describes the mass flux M.

The diffusion coefficient is described by

$$K_{\phi,e} = C_k l \sqrt{e}\,, \tag{4}$$

where $c_k = 0.5$ is a coefficient and l is the mixing length. The mixing length is proportional to the square root of the TKE (following Teixeira and Cheinet 2004)

$$l = \tau \sqrt{e}\,, \tag{5}$$

where $\tau = 600s$ is a time scale. Additionally, surface layer scaling is applied to assure a more realistic profile of the mixing length in the lower boundary layer $l = l + (kz - l)\exp(-z/\mu)$, where $k = 0.4$ is

the von Karman constant and $\mu \cong 50$ is the approximate depth of the surface layer. The dissipation term is parameterized with $D = C_e\, e^{3/2} / l_e$, with $C_e = 0.16$ and $l_e = l/2.5$.

Diagnostic equations for the updraft variables ϕ_u and w_u are following

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon\left(\phi_u - \bar{\phi}\right), \tag{6}$$

$$w_u \frac{\partial w_u}{\partial z} = -\varepsilon b_1 w_u^2 + b_2 B, \tag{7}$$

where ε is the lateral entrainment rate of the surrounding air into the updraft, $b_1 = 1$ and $b_2 = 2$ are coefficients, and $B = g\left(\theta_{v,u} / \bar{\theta}_v - 1\right)$ represents the buoyancy term. $\theta_{v,u}$ and $\bar{\theta}_v$ are virtual potential temperatures of the updraft and the surrounding air, respectively. The entrainment coefficient parameterizations will be discussed in the following sections.

Solving the updraft equation for ϕ_u requires initialization at the surface, which is done using

$$\phi_{u,s} = \bar{\phi}_s + \beta \frac{\overline{w'\phi'}_s}{\sqrt{e}}. \tag{8}$$

Here subscript s denotes the surface, or close to the surface values and $\beta = 0.3$ is a coefficient.

Entrainment coefficient formulations

The lateral entrainment of environmental air into updrafts affects the updraft evolution and dynamics. Highly entraining updrafts quickly loose their buoyancy before reaching the inversion. They transport surface layer characteristics into the middle of the boundary layer. Weakly entraining updrafts preserve their buoyancy throughout the PBL and penetrate the inversion contributing to the mass exchange at the interface and invigorating the PBL growth. A sample of boundary layer updrafts is presented in Fig. 1 that shows a vertical velocity cross-section obtained with a large eddy simulation (LES). Some updrafts are strong enough to reach the inversion level, which is about 2 km in Fig. 1, whereas other ascending plums diffuse earlier in the environment. Updraft entrainment plays an important role in controlling their lifetimes, therefore, adequate description of the lateral entrainment ε is essential in the mass-flux parameterization.

Parameterizatons of the lateral entrainment coefficient have been in use for several decades, particularly for cumulus convection. However, theoretical descriptions of this physical process are far from conclusive. Experimental investigations are also rare due to measurement difficulties. Even with the aid of such modern tools as LES it is not straightforward to analyze the lateral entrainment and to formulate physically based ε parameterizations.

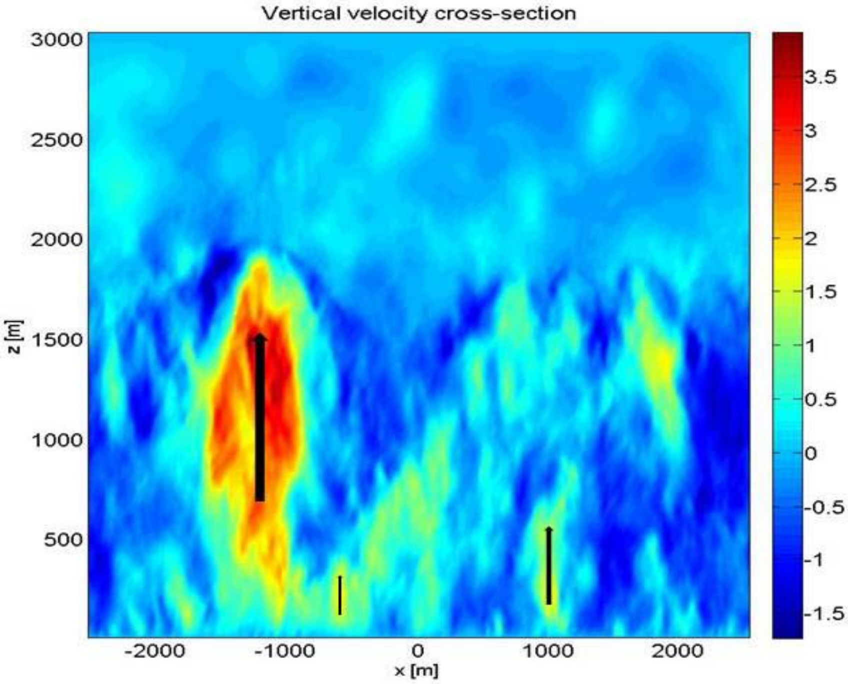

Figure 1 Vertical velocity cross-section after 2.5 hour of LES simulation. Vertical arrows localize some of the boundary layer updrafts. Top of the boundary layer is at about 2 km.

In a 1-D model (also partially in COAMPS) we use three different ε parameterizations to investigate how sensitive are the simulations to specific lateral entrainment formulations. The first approach is to describe ε as a function of the turbulent kinetic energy (e) through the use of an inverse of the mixing length (see Eq. 5)

$$\varepsilon_1 = \frac{1}{l} = \frac{1}{\tau\sqrt{e}} \,. \qquad (9)$$

This formulation is inspired by results found by Siebesma et al. (2007) that entrainment is determined by the dominant eddy size at height *z*, which can be also represented by the length scale *l*. The specific length scale formulation $l = \tau\sqrt{e}$ is adopted after Teixeira and Cheinet (2004). It is also possible to use different methods to derive *l*, without referring to *e*. For example, in the reference COAMPS simulations (described below) an alternative Blackadar's method is employed (Blackadar 1962). Here, for the purpose of the entrainment coefficient computations only, we use Eq. 9 with the turbulent kinetic energy.

Another entrainment parameterization uses a prescribed profile that depends on the height of the boundary layer

$$\varepsilon_2 = c_\varepsilon\left(\frac{1}{z+\Delta z} + \frac{1}{(z_* - z)+\Delta z}\right), \quad z < z_* \,, \qquad (10)$$

where z_* is the boundary layer height, $c_e = 0.5$ and Δz (vertical grid spacing) is added to reduce sensitivity to the vertical resolution. This formulation of ε is based on LES results and was previously used in Soares et al. (2004) and Siebesma et al. (2007). The disadvantage of this method is that it is sensitive to the boundary layer height, which by itself is ambiguously defined.

Finally, the third entrainment parameterization has the form

$$\varepsilon_3 = \frac{1}{\tau w_u}. \tag{11}$$

Here $\tau = 600s$ is a typical eddy turn-over timescale and w_u is derived from Eq. 7. This parameterization was proposed by Neggers et al. (2002) and was later used in Neggers et al. (2009).

Single column model results

General profiles

Figure 2 presents the temporal evolution of vertical profiles of potential temperature (θ_l and θ_{up}), specific humidity (Q_t), and the velocity components (*u* and *v*). Initial states along with results after 3 and 6 hours of the simulation are shown. Figure 3 shows source term contributions to the TKE prognostic equation at the 6th hour of the simulation (left panel) and the mass-flux and eddy-diffusivity terms at the 3rd and 6th hour of the simulation (right panel). All profiles are averaged over the last 30 minutes of the respective period.

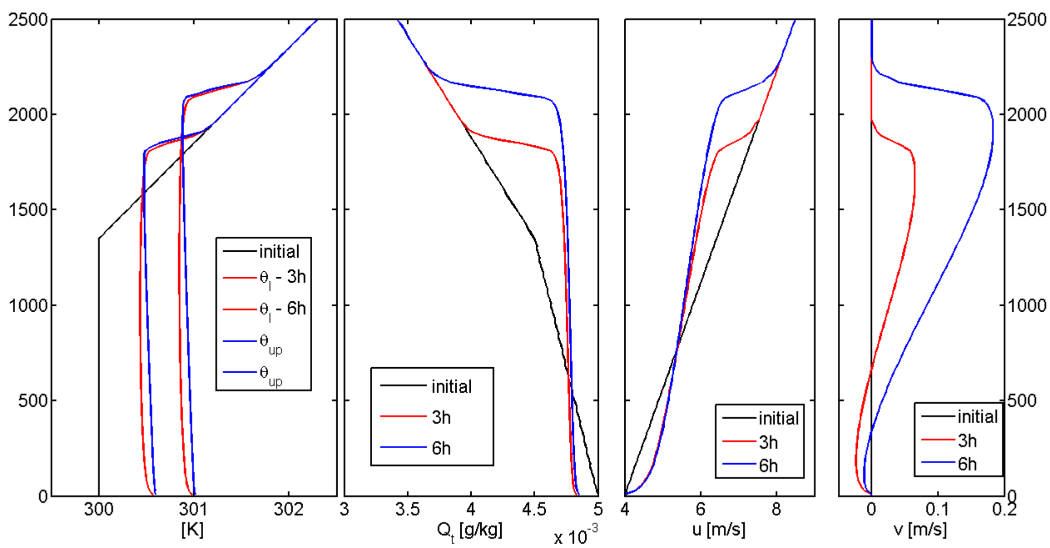

Figure 2 Vertical profiles of specific 1-D model variables. For further description see the text.

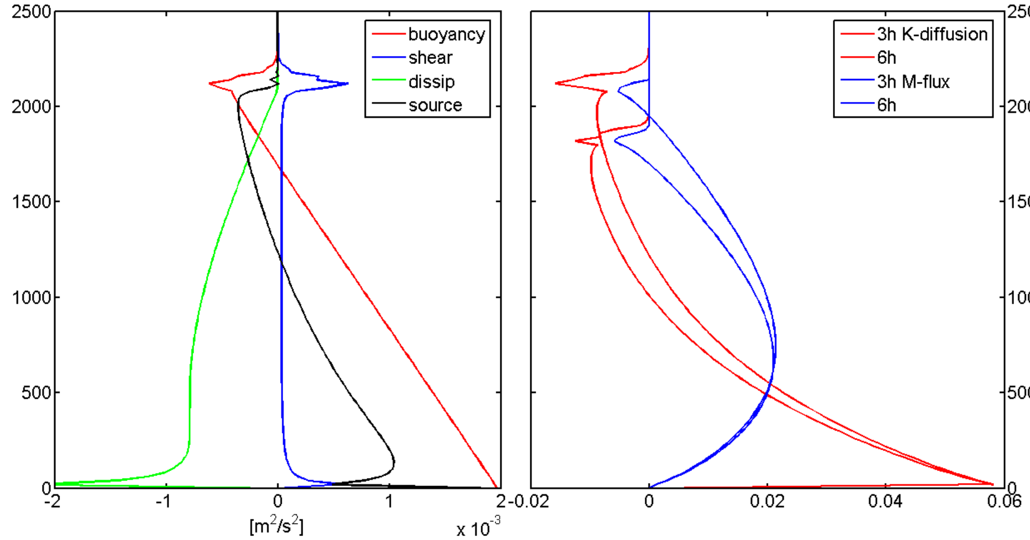

Figure 3 Vertical profiles of the TKE source terms. For further description see the text.

Sensitivity to lateral entrainment (ε) formulation

Figure 4 shows vertical profiles of $\overline{\theta}_l$ after 3 and 6 hours of model simulations obtained with the use of three different entrainment coefficient formulations described previously. Surface sensible heat flux is set to 0.06 Km/s. It is clear that the eddy-diffusivity parameterization (red line) does not properly generate a mixed layer state and a counter-gradient behavior in the upper part of the boundary layer, a characteristic typical of dry convective boundary layers. Adding the mass-flux component to the vertical fluxes improves the simulations, but the results are sensitive to the entrainment coefficient parameterization. Entrainment being a function of TKE provides results that are most similar to the ED simulation, only slightly improving the model. This approach is clearly not sufficient to generate the correct magnitude of entrainment; the mass-flux contribution is underestimated. On the other side of the spectrum, entrainment being inversely proportional to the updraft velocity generates the largest mass-flux, most vigorous entrainment and quickest boundary layer growth (black line). Prescribed entrainment (green line) creates more entrainment than the ED alone, but the profile is not sufficiently mixed and the counter-gradient characteristic is not clearly observed. Fig. 4 suggests that the entrainment parameterization is very important in the eddy-diffusivity/mass-flux parameterization. More studies need to be performed in order to find the most adequate lateral entrainment parameterization, but also to investigate other parameters in the EDMF approach.

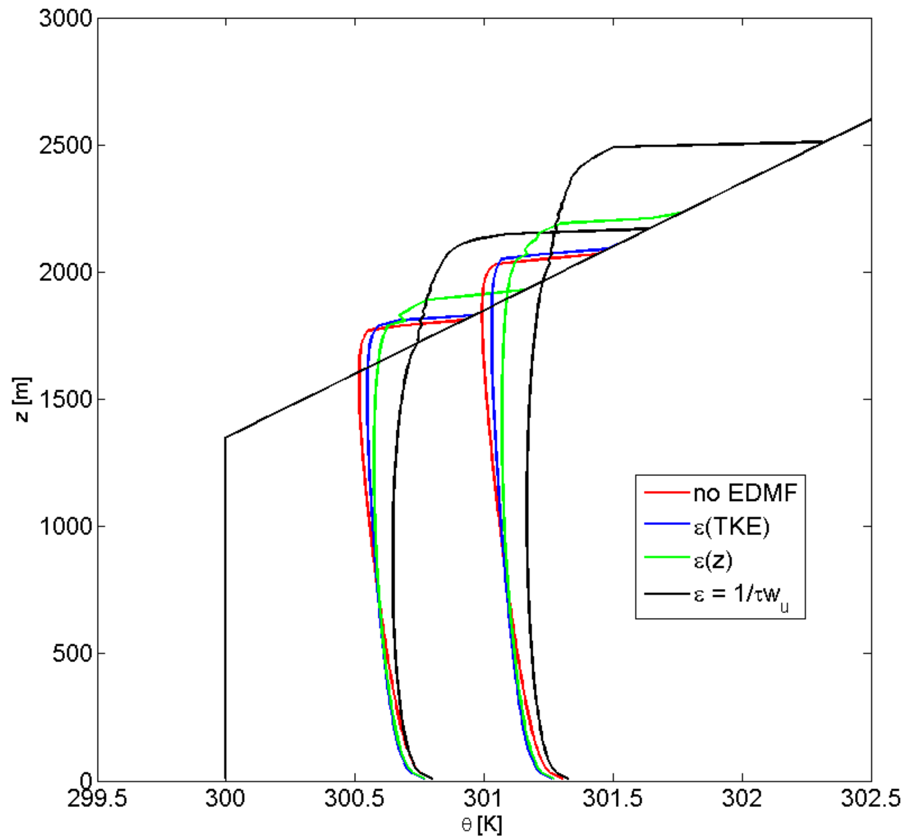

Figure 4 Vertical profiles of $\overline{\theta}_l$ obtained using different ε formulations. 1-D model results after 3 and 6 hours of the simulation.

EDMF in COAMPS

1. EDMF implementation in COAMPS

An EDMF scheme for scalar variables has been implemented in the COAMPS model in order to improve the vertical mixing in the planetary boundary layer. A new subroutine *edmfvar.F* that computes important parameterization variables was added into the model source code. Substantial modifications to vertical mixing routines (amixt.F, amixq.F) and a TKE prognostic equation routine (afore.F) were applied. Also, the mixing length formulation has been modified in COAMPS. The reference Blackadar (1962) parameterization was substituted with a parameterization based on TKE, taken after Teixeira and Cheinet (2004).

Key modifications in the representation of COAMPS physical processes include: a) adding the mass-flux component in the vertical diffusion routines for potential temperature and water vapor mixing ratio, b) adding mass-flux to the buoyancy source term in the TKE prognostic equation, and c) changing the mixing length parameterization.

Several options for parametrizing a lateral entrainment coefficient ε, an important parameter in the mass-flux formulation, have been incorporated into COAMPS. Parameterizations that carry most potential for improving COAMPS simulations are determined based on 1-D model results. They include prescribed ε as a function of height (e.g. Soares et al., 2004; Siebesma et al., 2007), and $\varepsilon = 1/\tau w_u$ (Neggers et al., 2002), where τ is a time scale and w_u is an updraft vertical velocity.

2. COAMPS simulations.

COAMPS simulations with the new boundary layer parameterization have been performed. The model domain was centered over southern Europe, with a horizontal resolution of 45 km and a default of 30 vertical levels. Results of the simulations were compared with radiosonde measurements carried out during the CICLUS experiment in July, 1998. The analysis allows direct assessment of model performance in a case of dry (no clouds) convective boundary layer.

Figure 5 presents CICLUS radiosonde observations (red lines) together with COAMPS simulations of potential temperature at the same location. Results from the reference COAMPS simulation (blue line) as well as from the simulation with a new EDMF approach (black line) are presented. The reference simulation only loosely follows the observed temperature profile. The modeled boundary layer is too cold and too shallow, the inversion height being several hundred meters below real values (e.g. 12h, 15h). This indicates that vertical mixing and entrainment are strongly underestimated in the reference COAMPS run. The EDMF parameterization follows much better the observed profiles, especially during daytime. The predicted inversion height is well represented; disagreement is observed only at the end of the simulation. Good prediction skill is somehow tampered by the inversion being not as sharp as in the observations. This could be partially due to low vertical resolution, which at this elevation is around a couple of hundred meters. Also, vertical mixing caused by the eddy-diffusivity and mass-flux components might be overestimated, leading to overestimated mixing between boundary layer and free atmosphere. Both aspects should be further investigated. Despite these drawbacks new EDMF approach improves COAMPS simulations of the dry convective boundary layer. It also carries a potential of constructing better and more physic-based cloud parameterization in COAMPS (see e.g. Neggers, 2009; Soares et al., 2004)

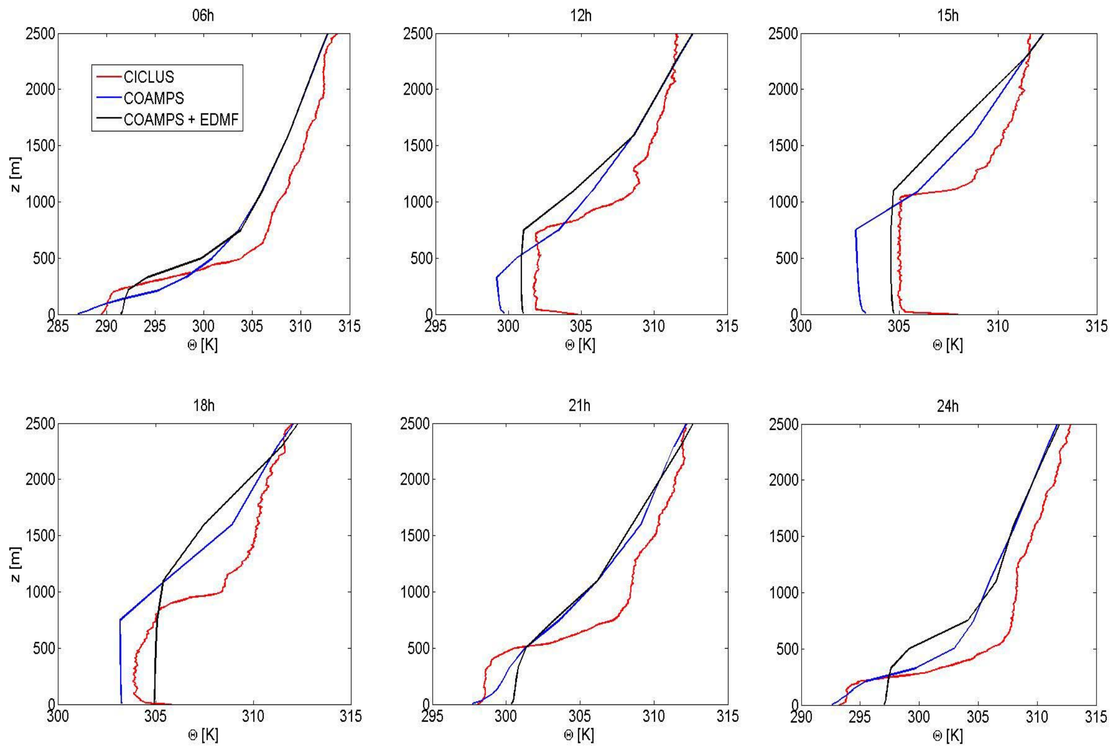

Figure 5 Potential temperature profiles measured with radiosondes during the CICLUS experiment on July 24, 1998 (red lines) and simulated by COAMPS: reference simulation (blue lines) and simulation with EDMF scheme (black line). Measurement hours denote local time (equivalent to UTC).

REFERENCES

Blackadar, A., 1962: The vertical distribution of wind and turbulent exchange in a neutral atmosphere. *J. Geophys. Res.*, **67**, 3095–3102.

Neggers, R. A., 2009: A dual mass flux framework for boundary layer convection. Part II: Clouds. *J. Atmos. Sci.*, **66**, 1489–1506.

Neggers, R. A., A. P. Siebesma, and H. J. J. Jonker, 2002: A multi-parcel model for shallow cumulus convection. *J. Atmos. Sci.*, **59**, 1655–1668.

Neggers, R. A. J., M. Köhler, and A. C. M. Beljaars, 2009: A Dual Mass Flux Framework for Boundary Layer Convection. Part I: Transport. *J. Atmos. Sci.*, **66**, 1465–1487.

Siebesma, A. P., P. M. M. Soares, and J. Teixeira, 2007: A combined eddy-diffusivity mass-flux approach for the convective boundary layer. *J. Atmos. Sci.*, **64**, 1230–1248.

Soares, P. M. M., P. M. A. Miranda, A. P. Siebesma, and J. Teixeira, 2004: An eddy-diffusivity/mass-flux parameterization for dry and shallow cumulus convection. *Q. J. R. Meteorol. Soc.*, **130**, 3365–3383.

Teixeira, J., S. Cheinet, 2004: A simple mixing length formulation for the eddy-diffusivity parameterization of dry convection. *Boundary-Layer Meteorol.*, **110**, 435–453.

Teixeira, J., J. P. Ferreira, P. M. A. Miranda, T. Haack, J. Doyle, A. P. Siebesma, and R. Salgado, 2004: A new mixing-length formulation for the parameterization of dry convection: implementation and evaluation in a mesoscale model. *Mon. Wea. Rev.*, **132**, 2698–2707.

IMPACT/APPLICATIONS

These results have an important potential future impact for the weather prediction capabilities of the US Navy after the implementation of these new parameterizations in the COAMPS model.

In addition it will be the first time that a unified parameterization of the marine boundary layer has ever been developed and implemented in a weather prediction model.

TRANSITIONS

The new EDMF parameterization will be proposed for a transition at FNMOC after implementation and adequate testing in the COAMPS model

RELATED PROJECTS

J. Doyle (NRL) is currently supported by an existing ONR project related to physical parameterizations and numerical techniques for high-resolution next-generation applications of COAMPS

PUBLICATIONS

- Kawai, H., and J. Teixeira, 2009: Probability Density Functions of Liquid Water Path of Marine Boundary Layer Clouds: Geographical and Seasonal Variations and Controlling Meteorological Factors, *Journal of Climate*, in press.

- Kahn, B. H., and J. Teixeira, 2009: A global climatology of temperature and water vapor variance scaling from the Atmospheric Infrared Sounder, *J. Climate*, **22**, 5558–5576, doi: 10.1175/2009JCLI2934.1.